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Studies in Statistical Optics - Theory & Application

Emil Wolf
UNIVERSITY OF ROCHESTER

07/29/2015
Final Report

Air Force Research Laboratory
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14. ABSTRACT
In this Final Report we summarize research carried out during the period of June 1, 2012 - May 31, 2015 under the sponsorship of the Air Force Office of Scientific Research under grant FA9550-12-1-0284. The results of our investigations were reported in 16 publications. Summaries of these publications are given on pages 5-8 of our report. The scientists who have participated in this research are listed on page 9.

15. SUBJECT TERMS
Coherence and statistical optics; scattering; propagation; reflection and refraction.

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Studies in Statistical Optics: Theory and Application

Grant No: FA9550-12-1-0284
June 1, 2012 – May 31, 2015

Final Report

Emil Wolf

The University of Rochester
Department of Physics and Astronomy
Rochester, New York

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July 27, 2015

UNIVERSITY OF ROCHESTER

DEPARTMENT OF PHYSICS AND ASTRONOMY

ROCHESTER, NEW YORK 14627

LIST OF CONTENTS

I. INTRODUCTION

This report presents a summary of research carried out during the period June 1, 2012 – May 31, 2015 under the sponsorship of the Air Force Office of Scientific Research, under grant FA9550-12-1-0284.

The results of our investigations were reported in several publications. They are listed on page 3-4. Summaries of these publications are given on page 5-8. Scientists who have participated in the research are listed on page 9.

II. LIST OF PUBLICATIONS RESULTING FROM RESEARCH SUPPORTED BY GRANT FA9550-12-1-0284 DURING THE PERIOD JUNE 1, 2012 – MAY 31, 2015

1. Fischer, T. van Dijk, T. D. Visser, and E. Wolf, “Coherence Effects in Mie Scattering”, *JOSA A*, **29**, 78-84 (2012).

2. M. Lahiri and E. Wolf, “Statistical Similarity and Cross-Spectral Purity of Stationary Stochastic Fields”, *Opt. Lett*., **37**, 963-965 (2012).

3. M. Lahiri and E. Wolf, “Spectral Changes of Stochastic Beams Scattered on a Deterministic Medium”, *Opt. Lett.*, **37**, pp. 2517-2519 (2012).

4. J. Rolland, K. Thompson, K. Lee, J. Tamkin Jr., T. Schmid, and E. Wolf, “Observation of the Gouy phase anomaly in astigmatic beams”, *Applied Optics*, **51**, No. 15, 2902-2908 (2012).

5. J. Horng, Y. Li, and E. Wolf, “Stokes beams formed by superposition of a completely unpolarized and a completely polarized Gaussian Schell-model beam” *Optics Commun.*, **285,** 4719-4726 (2012).

6. D. Kuebel, T. D. Visser, and E. Wolf, “Application of the Hanbury Brown-Twiss Effect to Scattering from Quasi-Homogeneous Media”, *Opt. Commun.*, **294,** 43-48 (2013).

7. M. Lahiri and E. Wolf, “Theory of Refraction and Reflection with Partially Coherent Electromagnetic Beams”, *Physical Review A*, **86**, 043815 (2012).

8. M. Lahiri and E. Wolf, “Change in Spatial Coherence of Light on Refraction and on Reflection”, *JOSA A*, **30**, 1107-1112 (2013).

9. S. B. Raghunathan, T. D. Visser, and E. Wolf, “Far-zone Properties of Electromagnetic Beams Generated by Quasi-homogeneous Sources”, *Opt. Commun.*, **295**, 11-16 (2013).

10. M. Lahiri and E. Wolf, “Negative Refraction of a Partially Coherent Electromagnetic Beam”, *Opt. Lett.*, **38**, 1407-1409 (2013).

11. M. Lahiri, “Quantum Theory of Coherence and Polarization of Light”, *Advances in Quantum Theory*, Chapter 4, p. 77 (In Tech, Croatia, 2012).

12. M. Lahiri, “Concept of Purity in the Theory of Optical Polarization”, *Opt. Letts.*, **38**, 866-868 (2013).

13. M. Lahiri and E. Wolf, "Propagation of Electromagnetic Beams of any State of Spatial Coherence and Polarization through Multilayered Stratified Media", *JOSA A*, **30**, 2547-2555 (2013).

14. E. Wolf, "Diffraction of Radiation of Any State of Spatial Coherence on Media with Periodic Structure", *Opt. Letts.*, **38**, 4023-4025 (2013).

15. M. Lahiri and E. Wolf, "Effect of Scattering on Cross-spectral Purity of Light", *Opt. Commun.*, **330**, 165-168 (2014).

16. M. Lahiri, "Coherence and Statistical Optics", Photonics:Scientific Foundations, Technology and Applications, Vol. 1, edited by David Andrews, John Wiley & Sons, 2015.

III. SUMMARIES OF PUBLICATIONS RESULTING FROM RESEARCH SUPPORTED BY GRANT FA9550-12-1-0284 DURING THE PERIOD JUNE 1, 2012 – MAY 31, 2015.

1. **Fischer, T. van Dijk, T. D. Visser, and E. Wolf, "Coherence Effects in Mie Scattering", *JOSA A*, 29, 78-84 (2012).**
The scattering of a partially coherent beam by a deterministic, spherical scatterer is studied. In particular, the Mie scattering by a Gaussian Schell-model beam is analyzed. Expressions are derived for (a) the extinguished power, (b) the radiant intensity of the scattered field, and (c) the encircled energy in the far field. It is found that the radiant intensity and the encircled energy in the far field depend on the degree of coherence of the incident beam, whereas the extinguished power does not.

2. **M. Lahiri and E. Wolf, "Statistical Similarity and Cross-Spectral Purity of Stationary Stochastic Fields", *Opt. Lett.*, 37, 963-965 (2012).**
In practical situations, one often generates a beam by superposition of two or more light beams. The beam generated by superposition displays, in general, different spectral properties than do the original beams. However, there are some optical beams, called cross-spectrally pure beams, which can generate a light beam of identical spectral distribution on superposition. The relationship between cross-spectral purity and spatial coherence has been the subject of investigations for some time. Recently, a concept of so-called statistical similarity has been introduced which provides a new way to elucidate complete spatial coherence. In this Letter, we discuss some implications of statistical similarity of an optical field on its cross-spectral purity.

3. **M. Lahiri and E. Wolf, "Spectral Changes of Stochastic Beams Scattered on a Deterministic Medium", *Opt. Lett.*, 37, pp. 2517-2519 (2012).**
It is well known that scattering of a polychromatic plane wave by a random medium, i.e., by a medium whose refractive index varies randomly with position, may produce frequency shifts of spectral lines. It has been a common perception that a random medium is required for generation of such spectral shifts by scattering. In this Letter we show that such a phenomenon occurs even when the refractive index of the medium is a deterministic function of position. We also show that this phenomenon may be used to obtain information about the structure of a deterministic medium.

4. **J. Rolland, K. Thompson, K. Lee, J. Tamkin Jr., T. Schmid, and E. Wolf, "Observation of the Gouy phase anomaly in astigmatic beams", *Applied Optics*, 51, No. 15, 2902-2908 (2012).**
The Gouy phase anomaly, well established for stigmatic beams, is validated here for astigmatic beams. We simulate the predicted Gouy phase anomaly near astigmatic foci using a beam propagation algorithm integrated within lens design software. We then compare computational results with experimental data acquired using a modified Mertz–Sagnac interferometer. Both in simulation and in experiment, results show that a $\pi/2$-phase change occurs as the beam passes through each of the astigmatic foci, experimentally validating results derived in a recent paper by Visser and Wolf [Opt. Commun. 283, 3371–3375 (2010)].

5. **J. Horng, Y. Li, and E. Wolf, "Stokes beams formed by superposition of a completely unpolarized and a completely polarized Gaussian Schell-model beam" *Optics Commun.*, 285, 4719-4726 (2012).**

Analytic expressions and computed examples are given to elucidate the coherence and polarization properties of Stokes beams, i.e. beams formed by superposition of a completely unpolarized and a completely polarized electromagnetic Gaussian Schell-model beam. We found that superposition of such two beams cannot form a Stokes beam with a constant state of polarization on propagation. An additional constraint on the source plane parameters of the two Gaussian Schell-model beams is proposed. The resultant Stokes beam with a constant state of polarization on propagation is found to be a Gaussian Schell-model beam with the same variances as the two constituent Gaussian Schell-model beams. However, the modulus of the Gaussian intensity distributions across the source planes of these beams may be different.

6. **D. Kuebel, T. D. Visser, and E. Wolf, "Application of the Hanbury Brown-Twiss Effect to Scattering from Quasi-Homogeneous Media",** ***Opt. Commun.*****, 294, 43-48 (2013).**
The scattering from a wide class of random scatterers, so-called quasi homogeneous scattering media, is studied by the use of the Hanbury Brown–Twiss effect. In particular the two-point correlation of intensity fluctuations and their variance in the far field are analyzed. A new reciprocity relation is derived, and expressions for the correlation of intensity fluctuations for several different types of scattering potentials are obtained. The results indicate the possibility of distinguishing, for example, hollow scatterers from solid ones.

7. **M. Lahiri and E. Wolf, "Theory of Refraction and Reflection with Partially Coherent Electromagnetic Beams",** ***Physical Review A*****, 86, 043815 (2012).**
Laws of refraction and reflection of light are governed by the classic Fresnel formulas. These formulas are not applicable to partially coherent light. We develop a general theory of refraction and reflection of electromagnetic beams of any state of coherence. We find that coherence properties of such beams change, in general, on refraction and on reflection at a planar interface.

8. **M. Lahiri and E. Wolf, "Change in Spatial Coherence of Light on Refraction and on Reflection",** ***JOSA A*****, 30, 1107-1112 (2013).**
Partially coherent light beams are encountered both in classical and in quantum optics. In this paper, we propose a novel technique for controlling coherence properties of such beams in laboratory environment. The technique is based on the fact that coherence properties of partially coherent electromagnetic beams, in general, change on refraction and on reflection, and that the changes can be controlled by varying the angle of incidence.

9. **S. B. Raghunathan, T. D. Visser, and E. Wolf, "Far-zone Properties of Electromagnetic Beams Generated by Quasi-homogeneous Sources",** ***Opt. Commun.*****, 295, 11-16 (2013).**
We derive expressions for the far-zone properties of electromagnetic beams generated by a broad class of partially coherent sources, namely those of the quasi-homogeneous type. We use these reciprocity relations to study the intensity distribution, the state of coherence and the polarization properties of such beams.

10. **M. Lahiri and E. Wolf, "Negative Refraction of a Partially Coherent Electromagnetic Beam",** ***Opt. Lett.*****, 38, 1407-1409 (2013).**

A theory of usual (positive) refraction of partially coherent electromagnetic beams has been developed recently. In this Letter, we discuss the theory of negative refraction of a partially coherent electromagnetic beam. We show that negative refraction can produce change in spatial coherence of such a beam.

11. **M. Lahiri, "Quantum Theory of Coherence and Polarization of Light, *Advances in Quantum Theory*, Chapter 4, p. 77 (In Tech, Croatia 2012).**
The article presents a review of recent results obtained in the quantum theory of optical coherence and optical polarization. The emphasis is on coherence theory in the space-frequency domain. Polarization properties of photons in an interference experiment are also discussed, from the viewpoint of wave-particle duality.

12. **M. Lahiri, "Concept of Purity in the Theory of Optical Polarization", *Opt. Letts.*, 38, 866-868 (2013).**
It was shown some time ago that the space-time and the space-frequency degrees of polarization of a stochastic electromagnetic beam are not equivalent to each other. It is not possible, in general, to obtain a formal relationship between them. In this Letter, we discuss certain conditions under which they are directly related. These conditions lead to the concept of polarization-purity. If an optical beam obeys these conditions, its space-frequency degree of polarization has the same value at all frequencies present in the spectrum, and the value is equal to the space-time degree of polarization.

13. **M. Lahiri and E. Wolf, "Propagation of Electromagnetic Beams of any State of Spatial Coherence and Polarization through Multilayered Stratified Media", *JOSA A*, 30, 2547-2555 (2013).**
We present a theory of propagation of a partially coherent and partially polarized electromagnetic beam through a multilayered stratified medium. The analysis shows that spatial coherence and polarization properties of the beam change, in general, on propagation through such a medium. We illustrate the results by example.

14. **E. Wolf, "Diffraction of Radiation of Any State of Spatial Coherence on Media with Periodic Structure", *Opt. Letts.*, 38, 4023-4025 (2013).**
A general formula is derived for the spectral density distribution in the far zone, produced by the diffraction of a beam of any state of spatial coherence on a medium with a spatially periodic structure. The formula may be used to determine the structure of crystals from the diffraction of partially coherent x-ray beams.

15. **M. Lahiri and E. Wolf, "Effect of Scattering on Cross-spectral Purity of Light", *Opt. Commun.*, 330, 165-168 (2014).**
The concept of cross-spectral purity was introduced by Mandel in connection with the modulation of spectral distribution of optical fields in superposition experiments. It is now known that spectral distribution of light can also change on scattering. We investigate the effect of scattering on cross-spectral purity. We show that the purity is, in general, not preserved on scattering. We also discuss some conditions under which it can be preserved at certain pairs of points in the far-zone.

16. **M. Lahiri, "Coherence and Statistical Optics", Photonics: Scientific Foundations, Technology and Applications, Vol. 1, edited by David Andrews, John Wiley & Sons,**

2015. This article presents a review of coherence properties and of statistical properties of light.

IV. SCIENTIFIC COLLABORATORS

In addition to Professor Emil Wolf, the Principal Investigator for this grant, the following scientists have taken part in the research:

FISHER, D.	Research and Technology Directorate, NASA Glenn Research Center, Cleveland, Ohio 44135, USA
HORNG, J.	Department of Electro-Optical Engineering, National United University, No.1, Lien-Da, Kung-Ching Li, Miao-Li, Taiwan 360, ROC
KUEBEL, D.	Department of Physics and Astronomy, University of Rochester, Rochester, NY
LAHIRI, M.	Department of Physics and Astronomy, University of Rochester, Rochester, NY and IQOQI, and Faculty of Physics, Boltzmanngasse 3, 1090 Vienna, Austria
LEE, K.	The Institute of Optics, University of Rochester, 275 Hutchison Road, Rochester, New York 14627, USA
LI, Y.	P.O. Box 975, Great River, NY 11739, USA
NEVINS, T.	Department of Physics and Astronomy, University of Rochester, Rochester, NY
RAGHUNATHAN, S.B.	Faculty of Electrical Engineering, Mathematics and Computer Science, Delft University of Technology, Delft, The Netherlands
ROLLAND, J.	The Institute of Optics, University of Rochester, 275 Hutchison Road, Rochester, New York 14627, USA
SCHMID, T.	The Institute of Optics, University of Rochester, 275 Hutchison Road, Rochester, New York 14627, USA
TAMKIN, J.	The Institute of Optics, University of Rochester, 275 Hutchison Road, Rochester, New York 14627, USA
THOMPSON, K.	Synopsys, Inc., 3 Graywood Lane, Pittsford, New York 14534, USA
VAN DIJK, T.	Graduate Student, Department of Physics and Astronomy, Free University, Amsterdam, The Netherlands
VISSER, T.	Professor, Department of Physics and Astronomy, Free University, Amsterdam, The Netherlands

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The full name of the principal investigator on the grant or contract.

Dr. Emil Wolf

Program Manager
The AFOSR Program Manager currently assigned to the award

Dr. Arje Nachman

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Abstract

Our research has been concerned with statistical properties of radiation in scattering processes which resulted in publications dealing with coherence effects in Mie scattering. We generalized the well-known Gouy phase anomaly from stigmatic to astigmatic beams. We extended the theory of refraction and reflection of electromagnetic beams of any state of spatial coherence. We presented new results relating to the concept of purity and introduced the concept of polarization purity. We analyzed spectral changes of stochastic beams, generated on deterministic media. Propagation of light beams through multi-layered stratified media was studied. Also, effects of scattering on cross-spectral purity of light was studied.

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1. Fischer, T. van Dijk, T. D. Visser, and E. Wolf, “Coherence Effects in Mie Scattering”, JOSA A, 29, 78-84 (2012).

2. M. Lahiri and E. Wolf, “Statistical Similarity and Cross-Spectral Purity of Stationary Stochastic Fields”, Opt. Lett., 37, 963-965 (2012).

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16. M. Lahiri, “Coherence and Statistical Optics”, Photonics:Scientific Foundations, Technology and Applications, Vol. 1, edited by David Andrews, John Wiley & Sons, 2015.

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